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TADEUSZ CHMIELEWSKI*, PIOTR GÓRSKI*

REVIEW OF SOME RESEARCH ON THE FULL-SCALE MONITORING OF CIVIL ENGINEERING STRUCTURES USING GPS

PRZEGLĄD WYBRANYCH BADAŃ DOTYCZĄCYCH MONITOROWANIA KONSTRUKCJI BUDOWLANYCH ZA POMOCĄ TECHNIKI GPS

Abstract

The static and dynamic deformation monitoring of engineering structures has been a matter of concern for engineers for many years. This paper provides a review of research and development activities from 1993 in the field of bridges, tall buildings, and tower health monitoring using GPS. Firstly, early pioneering applications of GPS to measure the structural vibrations of these structures and the assessment of the measurement accuracy of GPS are briefly described. The progress on monitoring the displacements and dynamic characteristics of bridges and tall structures, caused by traffic loads, wind, and the combined influence of solar radiation and daily air temperature variations, is then presented.

Keywords: *Global Positioning System (GPS), measurement accuracy, displacement monitoring, bridges, tall buildings and towers*

Streszczenie

Monitorowanie statycznych i dynamicznych przemieszczeń konstrukcji budowlanych jest przedmiotem zainteresowań inżynierów od wielu lat. W artykule przedstawiono przegląd badań i rozwój od 1993r. techniki GPS w monitorowaniu stanu technicznego konstrukcji mostowych, wysokich budowli i wież. Opisano pionierskie zastosowania systemu GPS do pomiarów drgań wymienionych konstrukcji budowlanych i badania dokładności tego systemu pomiarowego. Przedstawiono rozwój techniki GPS w monitorowaniu przemieszczeń i badaniu charakterystyk dynamicznych mostów i wysokich konstrukcji, poddanych działaniom wywołanym ruchem komunikacyjnym, wiatrem, nasłonecznieniem i dobową zmianą temperatury powietrza.

Słowa kluczowe: Globalny System Pozycyjny (GPS), dokładność pomiaru, monitorowanie przemieszczeń, mosty, wysokie budynki i wieże

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[*] Department of Civil Engineering, Opole University of Technology, Poland.

1. Introduction

The static and dynamic deformation monitoring of engineering structures has been a matter of concern for engineers for many years. Examples of deformation behaviour in engineering structures are historical full-scale experiments on the Eiffel Tower, the Empire State Building, the Stuttgart TV Tower and several others. These measurements have not only provided important clues for theoretical calculations but also provided the verification needed before a theory could be announced as being successful.

This paper provides an overview of the applications of the Global Positioning System (GPS) in monitoring engineering structures during the last twenty years. These applications have become a useful tool for measuring and monitoring the static, quasi-static, and dynamic responses in civil engineering structures exposed to thermal expansions, the action of wind, earthquakes, traffic loads, or even people's excitation on footbridges.

2. Preliminary research

The first pioneering applications of GPS to measure the structural vibrations of tall structures and large cable-stayed bridges took place in the years 1993-1996. Lovse et al. [9] installed two GPS receivers on the Calgary Tower (completed in 1968). Two GPS receivers were used on the tower only to provide backup data in case one receiver would fail. These receivers on the tower were mounted on tripods near the base of the main communication antenna above the observation deck (Fig. 1). The reference receivers were located on a tripod on the roof of a low-rise (three-story) apartment building situated approximately 1 km north of the Tower. Data was collected at 10 Hz for about 15 min in the morning of 19 November 1993.

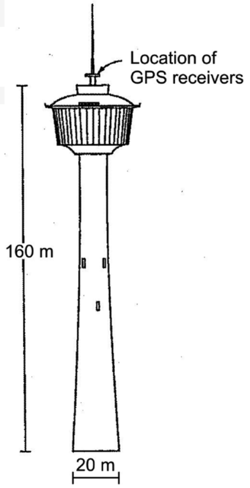

Fig. 1. The Calgary Tower and location of GPS receivers [9]

The analysis of the measured data gave the following results:

1) the Calgary Tower under wind loading vibrated with a natural frequency of about 0.3 Hz;
2) the N-S amplitude of displacement was approximately ±15 mm, and the E-W was ±5 mm.

The measured motion of the Calgary Tower using GPS receivers in both east-west and north-south directions is shown in Fig. 2 for a representative interval of 1 min.

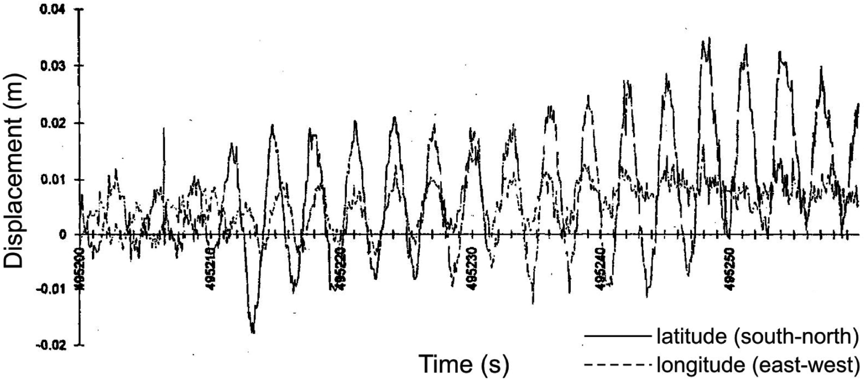

Fig. 2. Displacements of Calgary Tower [9]

Leach and Hyzak [8] reported their results as periodic movements on a large cable-stayed bridge, measured by GPS. Because the vertical movements, which had amplitudes in the order of ±30 mm, were caused by temperature changes rather than wind loading, a very slow sampling rate of one measurement every 10 s was sufficient to recover the movements.

Another example of preliminary research on the application of GPS in monitoring large-scale structures was conducted by Ashkenazi and Roberts [1]. Their paper describes the way in which the UK Humber Bridge was monitored using a 'kinematic GPS'. A rover receiver was placed on the west side rail of the bridge deck, at the mid span. The reference receiver was placed on the top of the bridge control tower. A measured test was carried out on two days – the first test on 7 March 1996, and the second on 7 May 1996. During the first test, the wind was fairly low and generally from the north-east along the length of the bridge. The authors have shown the results of the longitudinal, vertical, and lateral movements of the bridge deck, obtained from a selected period of time lasting 15 min. This was shown only for illustrative purposes. These tests were carried out only as a feasibility study of the kinematic GPS techniques for the in-situ monitoring of the movements of the bridge, and not as a full-scale experiment of a structural deflection analysis.

3. Assessment of measurement accuracy of GPS

After the first feasibility studies, GPS technology became an emerging tool for full-scale measuring and monitoring both static and dynamic responses to ambient loads of longstanding structures. As a new method, GPS performance had to be thoroughly validated before its application as a full-scale test of structural displacement analysis. Many researchers [2, 4, 14, 18] carried out feasibility studies to investigate the following questions: (1) What is the accuracy of measurements of horizontal and vertical displacements? (2) What is the range and level of natural frequencies and mode shapes determined by GPS? (3) Does this accuracy depend on the frequency of recorded vibrations? (4) Can some of the first natural frequencies be detected from a single displacement record?

In order to answer these questions, many calibration tests were carried out by applying various kinds of equipment such as: an earthquake shake-simulator track; shaking platforms; slender structure simulating equipment; experimental apparatus consisting of one or three degree of freedom oscillators; rotating arm equipment.

The major outcome of these studies showed that GPS, advanced to record 10 samples per second (sps or Hz), could record vibrations with frequencies of 0.1 to 4 Hz with an accuracy ±0.5 cm horizontally and ±1 cm vertically.

The most recent paper which deals with the error properties of ultra-high-rate GPS data was published by Moschas and Stiros [12]. In this paper, the impact of the phase-locked loop (PLL) bandwidth on the noise and correlation of GPS measurements, sampled at 100 Hz, was investigated using short and long baselines, and stationary or moving GPS rovers recording vibrations with known characteristics relative to ‘true’ reference values. Data were collected under various satellite constellations using various values of PLL bandwidth, i.e. 25, 50, 100 Hz and were processed in differential mode using different software packages. The authors suggested that optimal results can be obtained using either a pre-set 50 Hz PLL bandwidth or a 100 Hz PLL bandwidth combined with a posteriori band-pass filtering of the coordinates. Such optimal results permitted an accurate recording with a standard deviation 4 mm horizontally and 7 mm vertically, and indicated that 100 Hz data are useful for monitoring high-frequency structural vibrations, and also strong earthquake and high-frequency movements from vehicles.

4. Monitoring vibrations in structures such as bridges, tall buildings and towers

Nakamura [13] described a field test using GPS conducted for about three weeks in March 1998 on a Japanese suspension bridge (with a main span of 720 m and two side spans of 330 m each) to measure the girder displacements induced by a strong wind. Two sets of GPS receivers were placed on the mid-span of the girder. The reference receiver was installed on a land office about 1 km away from the bridge’s centre. The rover and reference receivers recorded displacements at a rate of 1 sample per second (sps = 1 Hz). Accelerometers were also set at the same position as the GPS rover receivers and acceleration data in three directions was collected at the same time. The main results of the described test are as follows: 1) the natural frequencies obtained by GPS data in the lateral (first), vertical (first), longitudinal (first and second) directions and those obtained by accelerometers matched very well. In addition, these values agreed well with the values obtained analytically by the FEM and in the forced vibration tests; 2) the vertical displacement measured by GPS showed 24-hour periodic movements because of the temperature changes in the cable; 3) it may be concluded that GPS technology is reliable and useful in measuring the static and gust response behaviours of long span bridges.

Meng et al. [10] applied GPS array units and triaxial accelerometers in order to carry out a field test to record the response of the Wilford Bridge, a suspension footbridge over the River Trent in Nottingham. The footbridge response measurements to different excitations such as forced vibration excited by more than thirty people with a total mass of 2353 kg, as well as subsequent decayed free vibration and an ambient vibration caused by casual pedestrian traffic and a light wind loading were performed. Designing a proper digital filter for the extraction of structural dynamics parameters was an important aspect of the structural deformation analysis of this footbridge. Measurement time series in the format of coordinates or accelerations were filtered either to reduce the noise level or to split the measurements so that only the real signals to an allotted frequency band were the output for further analysis.

Tamura et al. [18] made two experiments to demonstrate the feasibility of real-time kinematic Global Positioning System (RTK-GPS) for measurements of the wind-induced response and its efficiency in measuring the displacement of a full-scale tower (108 m tall). In the first experiment, the accuracy of RTK-GPS in measurements of the sinusoidal displacements was examined using an electronic exciter. A GPS antenna was mounted on the measuring point of the exciter, and a wire displacement transducer was set to measure the actual displacement. Fig. 3 shows the set-up of the sinusoidal displacement tests. It was experimentally ascertained that when the vibration frequency was lower than 2 Hz and the vibration amplitude was larger than 2 cm, RTK-GPS results were very close to the actual displacement. The efficiency of RTK-GPS was then demonstrated in the full-scale measurement of the actual steel tower. The sketch of the steel tower and some results of the measurements are shown in Figs. 4, 5 and 6.

GPS offers great potential for the structural health monitoring (SHM) of tall buildings. Several tests have so far been conducted. Çelebi [3] made two preliminary tests to prove the technical feasibility of the application of GPS to monitoring tall buildings. The first test was performed with a standard stack steel bar to simulate a thirty to forty story flexible building. In the second test, they measured an ambient vibration (exposed to the wind and traffic noise) of a forty-four story building with a GPS unit temporarily deployed on its roof. The reference GPS unit was located within 500 m of the building. The signals were very noisy and the amplitudes very small (< 1 cm); therefore, the most common method to identify structural characteristics did not work. It was possible to identify the fundamental frequency of the building at 0.23 Hz.

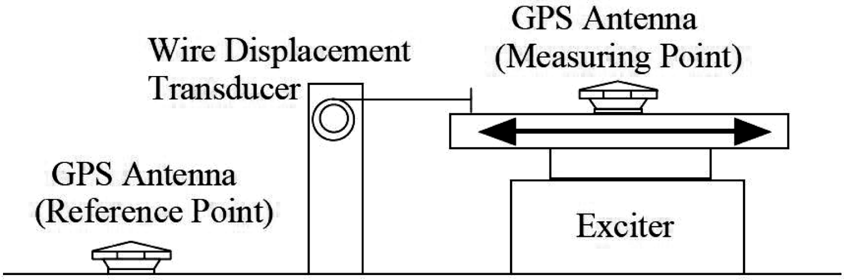

Fig. 3. Sketch of the experimental set-up of the sinusoidal vibration tests using an exciter [18]

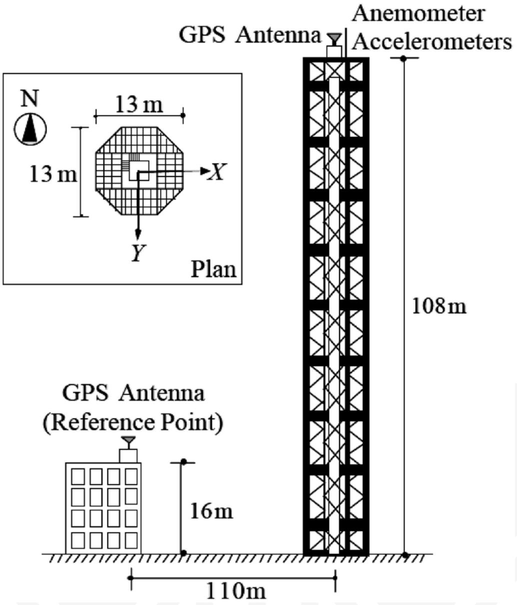

Fig. 4. A 108 m tall steel tower for full-scale measurements [18]

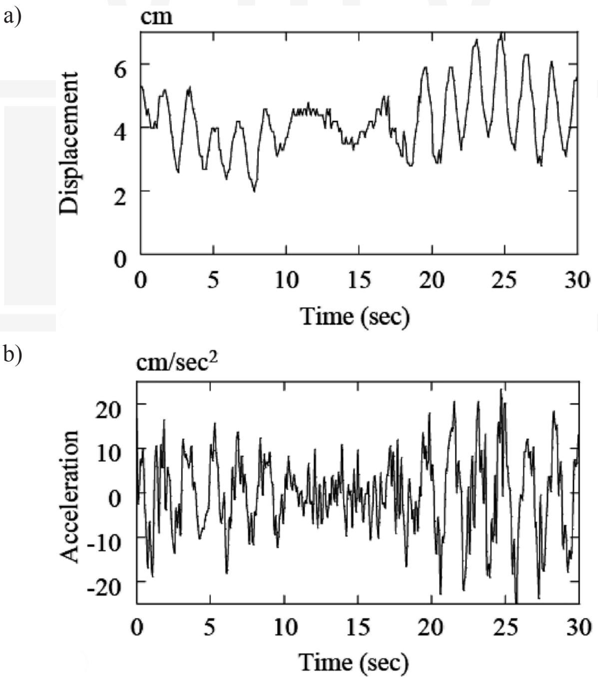

Fig. 5. Example of temporal variations of wind-induced responses of an actual steel tower during a typhoon: (a) RTK-GPS (Y-dir.) and (b) accelerometer (Y-dir.) [18]

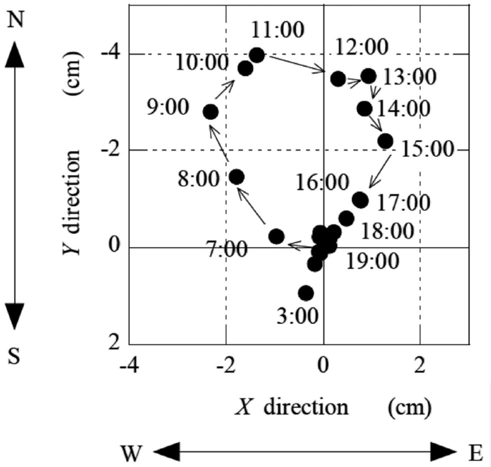

Fig. 6. Deformation of the tower caused by solar radiation and daily temperature variations [18]

Ogaja et al. [15] installed two Trimble 4700 units on the top of the Republic Plaza (280 m tall) in Singapore sampling at the rate of 1 Hz to measure the vibrations of the building due to the wind. Ogaja et al. [15, 16] used a pair of Leica GPS units installed on the Republic Plaza building again to generate a time series of the receiver positions. Chen et al. [5] conducted a field test employing two NovAtel Outrider DL RT2 dual frequency GPS units to measure the vibrations of the 384 m tall Di Wang building in Shenzen, China, under relatively strong wind conditions.

Kijewski-Correa et al. [6, 7] established a ‘Chicago Full-Scale Monitoring Program’ in 2001 to characterize the in-situ response of three tall buildings in order to verify design practices.

Breuer et al [2] examined field tests conducted on the Stuttgart TV tower to measure the displacements at the top of the tower caused by the wind and the combined influence of solar radiation and daily air temperature variations during different weather seasons and conditions. This paper presents the daily drift of the top of the Stuttgart TV Tower caused by solar radiation and daily air temperature variation during three GPS campaigns during different seasons. The daily elliptical path of the shift extends mainly in a west-east direction during summertime and in a northerly direction during winter. Fig. 7 shows the time-dependent records of the air temperature, the intensity of sun radiation and the air humidity during 4 days of measurements (4th–8th July 2006). The daily drift of the top of the Stuttgart TV Tower due to solar radiation and daily temperature variation, shown in Fig. 8, strongly depended on the meteorological conditions. The maximum displacement of the top towards the west appeared only during the first three days (4th–6th July), i.e. when solar radiation and daily air temperature variations were relatively high. During the final two days (7th–8th July), the positions of the top stabilized, indicating a reduced motion rate. This paper also presents the static and dynamic components (in the plane of the east-west and south-north directions) of the wind response during a thunderstorm (Fig. 9). For the wind response and for a sample rate equal to 2 sps, GPS was able to measure only the first natural frequency (0.191 Hz) of the Tower.

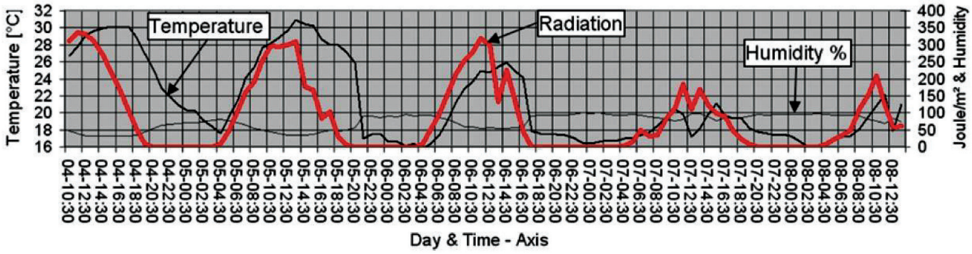

Fig. 7. The recorded temperature, the intensity of solar radiation and the humidity of the air during the GPS session (4th–8th July 2006) at the German Meteorological Station in Echterdingen, located 7 km from the Stuttgart TV Tower [2]

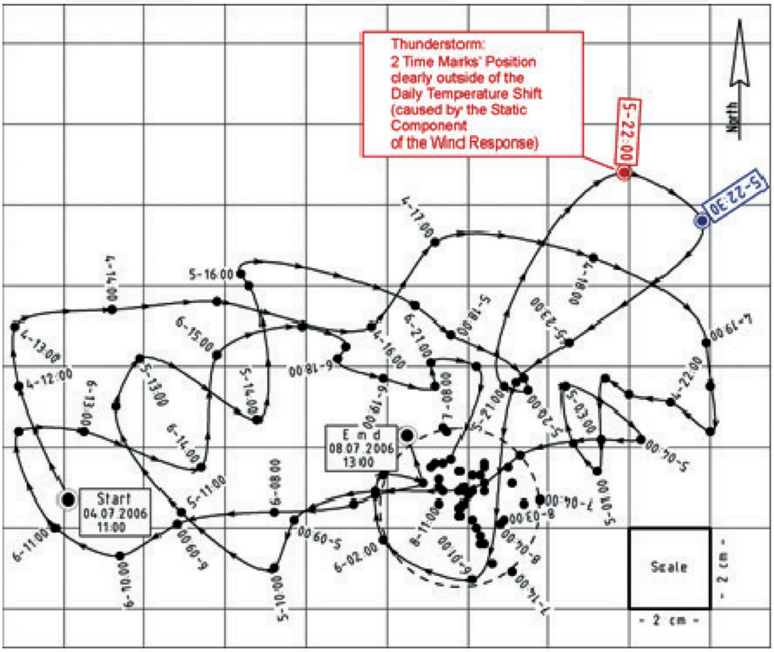
Thunderstorm:
2 Time Marks' Position
clearly outside of the
Daily Temperature Shift
(caused by the Static
Component
of the Wind Response)

Fig. 8. The Stuttgart TV Tower, daily drift of the top due to solar radiation and daily temperature variation with hourly positions and time marks (4th–8th July 2006). In the north-east of the ground plan, two outliers are shown, caused by a thunderstorm with wind from the south-west at a peak velocity of about 17 m/s [2]

Moschas and Stiros [11] presented a new technique to reconstruct displacement records of relatively rigid structures (natural frequency: 1<f<5 Hz). This technique was based on the double digital filtering of high-frequency (10 Hz) GPS recordings of an oscillation, constrained and assessed by independent accelerometer data. This technique was applied to the processing of noisy GPS measurements of vibrations of a 40 m long steel footbridge excited by the coordinated jumps of a group of people.

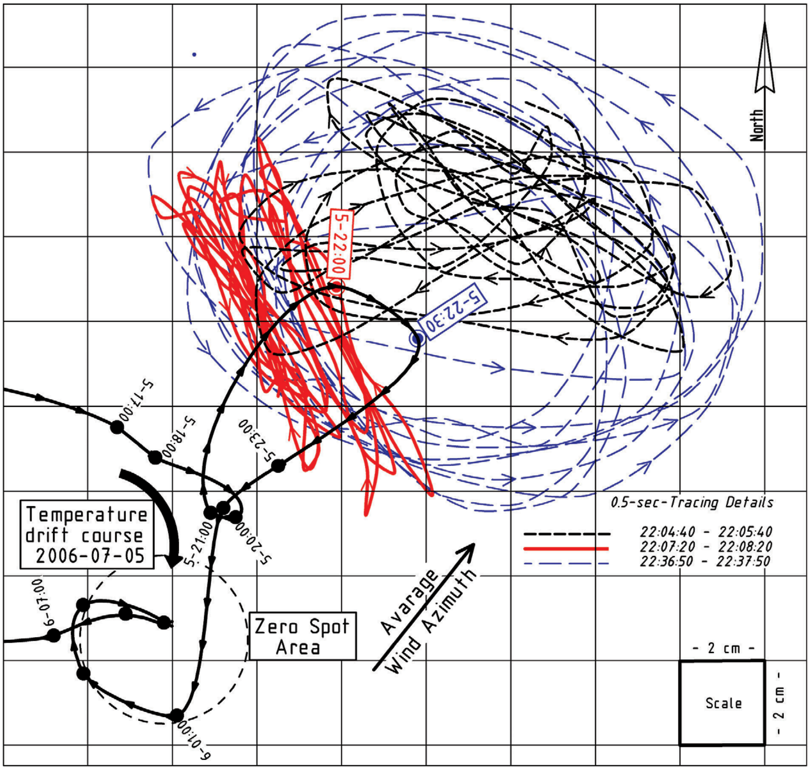

Fig. 9. The Stuttgart TV Tower, static and dynamic components of wind response during a thunderstorm producing an outline of the daily temperature drift (see Fig. 8). The wind from South-West with a peak velocity of about 17 m/s causes a north-east displacement (static component) of about 6 cm. The main direction of vibration is at a right angle to the wind direction with a displacement of 9–14 cm, 5th July 2006 [2]

5. Main characteristics in GPS monitoring technology

Although the GPS offers a useful tool for measuring static, quasi-static and dynamic responses of structures, it has its own limitations. The GPS satellite signals are susceptible to several kinds of error sources such as ionosphere and troposphere errors, receiver noise, multipath effects, satellite coverage and even GPS data sampling rates. During measurements, it is possible to eliminate or reduce (with mathematics and modelling) some of the troublesome GPS biases. However, two biases still remain that have not be eliminated, i.e. the geometric dilution of precision (GDOP) error, and the multipath effect (which occurs when duplicate satellite transmissions are received by the GPS receiver). The GDOP error is inherent in GPS technology and can be practically remedied through the addition of more satellites – this is now available by included more satellites from systems other than GPS, e.g. GNSS (Global Navigation Satellite System).

Regarding the application of GPS for the monitoring of structural vibrations, a sampling rate of 10 to 20 Hz only permits identifying the first natural frequency of common civil engineering structures, typically below 5 Hz. These sampling rates limit its capability for detecting higher mode signals of these structures.

The additional limitation is the price of GPS receivers which are high and hinder the application of GPS technology in practice.

In order to overcome the limitations mentioned above, it seems reasonable to apply an integrated sensor system consisting of GPS receivers combined with other sensors, i.e. accelerometers, laser scanners, displacement transducers, multi-waveform radars and fibre optic sensors. Such an integrated sensor system can increase the accuracy, reliability and effectiveness of the monitoring system.

6. Conclusions

1) In the last twenty years, the GPS with 10 Hz sampling rates has become a useful tool for measuring and monitoring static, quasi-static and dynamic responses in civil engineering structures exposed to settlement, gust-winds, earthquakes, thermal expansions traffic loads, and even some unforeseen events. These measurements allow the examination of both displacement levels and vibration characteristics such as natural frequencies, mode shapes, and damping ratios. These values are the key parameters when assessing the safety of flexible engineering structures. One should remember that the sampling rate of 10 Hz mostly permits us to identify the first natural frequency of the majority of civil engineering structures (below 5 Hz).
2) GPS can measure the total wind response, i.e. its dynamic fluctuating component and also a static component which is directly measured.
3) Ten years ago, a GPS sampling rate of 10 Hz was considered to be high. Recently, rates of 20, 50 or even 100 Hz have been used for some different kinematic applications. Further studies of the error properties of ultra-high-rate GPS data are needed in the near future.
4) In order to overcome the above limitations, it seems reasonable to apply an integrated sensor system consisting of the GPS receivers with other sensors, i.e. accelerometers, laser scanners, displacement transducers, multi-waveform radars and fibre optic sensors.

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